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Spatial variations of northeast monsoon rainfall over south peninsular India

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सार – यह अध्ययन दक्षिण प्रायद्वीपीय (SP) भारत पर पूर्वोत्तर मॉनसून (NEM) वर्षा की स्थानिक परिवर्तिता की जांच करता है जिसमें पांच मौसम संबंधी उपखंडों पर ध्यान केंद्रित किया गया है: तटीय आंध्र प्रदेश, रायलसीमा, तमिलनाडु, दक्षिण आंतरिक कर्नाटक और केरल। भारतीय उष्णकटिबंधीय मौसम विज्ञान संस्थान (IITM) से वर्षा के आंकड़ों का उपयोग करते हुए NEM अवधि (अक्टूबर-दिसंबर) के लिए ऋतुनिष्ठ वर्षा प्रवृत्ति का आकलन किया गया, मानकीकृत विचलनों के आधार पर सक्रिय और खराब मॉनसून वर्षों की पहचान की जाती है। मिश्र वर्षा मूल्य और प्रतिशत विचलन उपखंडों में एनईएम प्रदर्शन के बारे में जानकारी प्रदान करते हैं। विश्लेषण में प्रमुख मौसम संबंधी मापदंडों जैसे कि निम्न क्षोभमंडलीय हवाएं, सापेक्ष भंवर, और 1000 hPa, 850 hPa, और 200 hPa पर विचलन, 1948 से 2016 तक NCEP/NCAR पुनर्विश्लेषण डेटासेट का उपयोग करके पता लगाया गया है। NOAA (1974-2016) से आउटगोइंग लॉन्गवेव रेडिएशन (OLR) डेटा सक्रिय और खराब मॉनसून वर्षों के साथ जुड़े वायुमंडलीय परिसंचरण प्रवृत्ति को स्पष्ट करता है। निष्कर्ष बताते हैं कि सक्रिय NEM मौसम एसपी भारत और आसपास के समुद्रों पर नकारात्मक OLR विसंगतियों को प्रदर्शित करते हैं, जो विशेष रूप से आंध्र प्रदेश, रायलसीमा और तमिलनाडु के तटीय क्षेत्र में बढ़े हुए संवहनी गतिविधियों का संकेत देते हैं। इसके विपरीत, खराब मॉनसून सकारात्मक OLR विसंगतियां दर्शाता है, जो कम संवहनीय गतिविधि का संकेत देता है। हवा और अपसरण विसंगतियों से पता चलता है कि सक्रिय मॉनसून पूर्वी प्रवाह को मजबूत करता है और इंटरट्रॉपिकल कन्वर्जेंस ज़ोन (ITCZ) में नमी के परिवहन को बढ़ावा देता है, जिससे वर्षा में बढ़ोतरी होती है। खराब मॉनसून के दौरान, कमजोर पूर्वी हवाएँ और कम वायुमंडलीय अभिसरण कम वर्षा के साथ मेल खाते हैं। उल्लेखनीय रूप से, एल नीनो घटनाएं आम तौर पर एनईएम वर्षा को बढ़ाती हैं, जबकि ला नीना वर्षों में आम तौर पर कुछ अपवादों (वर्ष 2016) को छोड़कर वर्षा में कमी होती है।

ABSTRACT. This study investigates the spatial variability of Northeast Monsoon (NEM) rainfall over South Peninsular (SP) India, focusing on five meteorological subdivisions: Coastal Andhra Pradesh, Rayalaseema, Tamil Nadu, South Interior Karnataka, and Kerala. Using rainfall data from the Indian Institute of Tropical Meteorology (IITM), seasonal rainfall patterns are assessed for the NEM period (October-December), identifying active and poor monsoon years based on standardized departures. Composite rainfall values and percentage deviations provide insights into NEM performance across subdivisions. The analysis also explores key meteorological parameters, including lower tropospheric winds, relative vorticity and divergence at 1000 hPa, 850 hPa, and 200 hPa, using NCEP/NCAR Reanalysis datasets from 1948 to 2016. Outgoing Longwave Radiation (OLR) data from NOAA (1974–2016) further elucidate atmospheric circulation patterns associated with active and poor monsoon years. Findings reveal that active NEM seasons display negative OLR anomalies over SP India and surrounding seas, indicating enhanced convection, particularly in Coastal Andhra Pradesh, Rayalaseema and Tamil Nadu. Conversely, poor monsoons show positive OLR anomalies, signalling reduced convective activity. Wind and divergence anomalies highlight that active monsoons strengthen easterly flows and promote moisture transport to the Intertropical Convergence Zone (ITCZ), amplifying rainfall. During poor monsoons, weakened easterlies and reduced atmospheric convergence correspond with diminished rainfall. Notably, El Niño events generally enhance NEM rainfall, while La Niña years typically result in deficits, with some exceptions, such as in 2016.

Key words – Indian Monsoon, Rainfall, Relative vorticity, Divergence, Outgoing long wave radiation, Zonal wind.

1. Introduction

The India Meteorological Department (IMD) designates the period from October to December as the Northeast Monsoon (NEM) season, during which the primary rainfall zone shifts to southern India, Sri Lanka, and surrounding oceanic regions. Unlike the Southwest Monsoon, the NEM has a shallower vertical extent and a more stable pattern, contributing approximately 11% of India's annual rainfall. In southern Indian districts, the NEM provides 30-60% of annual rainfall, which is crucial for key crops like rice and maize, particularly in Tamil Nadu and Andhra Pradesh (Naidu *et al*., 2010, 2012; Rajeevan *et al*., 2012).

NEM rainfall exhibits considerable variability across intraseasonal, interannual and long-term timescales (Rajeevan *et al*., 2012; Dimri *et al*., 2016; Ramaswamy, 1972; Dhar and Rakhecha, 1983; Zubair and Ropelewski, 2006). Most studies have traditionally used a fixed October-December period for NEM analysis (Krishna Rao and Jagannathan, 1953; Raj and Jamadar, 1990; Singh and Sontakke, 1999). However, this fixed period may miss potential fluctuations in the season's actual length. The subtropical westerly jet, carrying western disturbances, influences the Indian subcontinent's weather, with implications for NEM rainfall variability (Das *et al*., 1995).

El Niño and La Niña events, central to NEM variability, generally increase and decrease rainfall over southern India, respectively (Khole and De, 2003; Misra and Bhardwaj, 2019). During El Niño, the NEM is often normal or above normal in Tamil Nadu due to enhanced low-pressure systems (Sridharan and Muthuswamy, 1990; De and Mukhopadhyay, 1999). Conversely, La Niña years show weaker monsoon circulation. Other climatic oscillations also play a role; for example, the Indian Ocean Dipole's positive phase, marked by warm western Indian Ocean SSTs, is linked to enhanced NEM rainfall (Kripalani and Kumar, 2004). The North Atlantic Oscillation (NAO) shows an inverse relationship with NEM rainfall (Balachandran *et al*., 2006).Overall, studies suggest that ENSO, the Indian Ocean Dipole, and SSTs in key regions like NINO3.4 are valuable predictors of NEM rainfall variability, with recent years showing a stronger correlation between ENSO and NEM patterns (Revadekar *et al*., 2008; Prasanna *et al*., 2019; Singh *et al*., 2017).

South Peninsular India experiences significant rainfall from various synoptic weather systems, particularly tropical cyclones, depressions and coastal convergence zones (Jayanthi and Govindachari, 1999). During the Northeast Monsoon (NEM), heavy rainfall often occurs in short, intense spells (De *et al*., 1992). Coastal regions, in particular, depend on cyclonic storms as a major source of rainfall (Bhaskar Rao *et al*., 2001). The intensity of this precipitation is influenced by both thermodynamic and dynamic climate factors, with warming trends contributing to an increase in extreme rainfall events (Kunkel *et al*., 2013; Koteswararao *et al*., 2020).

Koteswararao *et al*. (2020) explored the variability of NEM rainfall across South Peninsular India, particularly under warming scenarios, highlighting shifts in precipitation extremes. Their study also examined spatial differences in NEM rainfall during active and poor monsoon years, focusing on five key subdivisions: Coastal Andhra Pradesh, Rayalaseema, Tamil Nadu, South Interior Karnataka, and Kerala. To understand atmospheric drivers, the study analyzed Outgoing Longwave Radiation (OLR), zonal wind patterns, divergence, and relative vorticity, assessing both their distributions and anomalies during active and poor NEM years.

This research aims to enhance understanding of NEM rainfall variability over South Peninsular India, providing insights into how atmospheric factors contribute to rainfall distribution across subdivisions. Such information is critical for forecasting and managing water resources and agriculture, as well as for anticipating changes in extreme weather patterns due to climate variability.

2. Data and methodology

The area-weighted rainfall amounts over SP India, comprising five meteorological subdivisions are coastal AP, Rayalaseema, Tamil Nadu, South Interior Karnataka and Kerala collected from the IITM Pune website (www.tropmet.res.in) for the period 1871-2016 are used to identify good and poor monsoon years and compute the mean, standard deviation (SD) and coefficient of variation (CV) (Wilks, 2006).

$$\text{Mean rainfall}\left(\overline{X}\right)=\sum \frac{X}{N} \tag{1}$$

$$\sigma=\sqrt{\sum \frac{\left(X_i-\mu\right)^2}{N}} \tag{2}$$

$$CV=\frac{\sigma}{\mu} \tag{3}$$

σ = rainfall standard deviation

N = number of years

x_i = each year rainfall value

μ = the rainfall mean

The normalized values (Z) are calculated by using the formula,

$$Z = \frac{x_i - \mu}{\sigma} \tag{4}$$

If Z is greater than or equal to 1, the corresponding monsoon is considered as an active monsoon and if Z is less than or equal to -1, it is taken as a weak monsoon.

Then the behaviour of different meteorological parameters for both active and poor monsoon seasons is studied. The mean OLR pattern for the domains 5° to 40 °N, 65 °E to 100 °E in the northeast monsoon season for the period 1974-2016 is prepared from data sources on the NOAA website. Then the composite OLR anomalies for both the poor and active northeast monsoons are prepared separately. The anomalies are obtained by subtracting the mean values from the raw values.

Further, the mean zonal wind patterns, relative vorticity and divergence patterns for 1000 hPa, 850 hPa, and 200 hPa levels for domains 0 to 60 °N, 40 °E to 120 °E were considered for the NEM season for the period 1948-2016. The data source from the NCEP/NCAR Reanalysis (https://psl.noaa.gov/data/gridded/data.ncep.reanalysis.html).

$$\varsigma = \frac{\partial V}{\partial x} - \frac{\partial U}{\partial y} \tag{5}$$

$$D = \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} \tag{6}$$

where,

ζ is relative vorticity, D is Divergence

U represents Zonal wind component

V represents Meridional wind component

The anomaly zonal wind patterns are also evaluated separately for active and poor NEM seasons.

TABLE 1

Mean rainfall amounts in mm, the SD and coefficient of variation for northeast monsoon

Subdivision/area	Mean rainfall in mm	SD	CV (%)
S P India	347	93	27
Coastal AP	376	145	38
Rayalaseema	208	87	42
Tamil Nadu	458	144	31
S.I. Karnataka	215	85	40
Kerala	479	149	31

3. Results and discussions

3.1. *Mean rainfall and good and poor monsoon years*

The mean rainfall amounts, along with the corresponding standard deviation (SD) and coefficient of variation (CV), are presented in Table 1. The long-term mean rainfall during the NEM season for South Peninsular (SP) India is 347 mm, with an SD of 93 mm (27% CV). Kerala experiences the highest amount of rainfall, averaging 479 mm with an SD of 149 mm (31% CV). Tamil Nadu follows with 458 mm of rainfall and an SD of 144 mm (31% CV). Coastal Andhra Pradesh receives 376 mm of rainfall with a high SD of 145 mm (38% CV). South Interior Karnataka and Rayalaseema receive 215 mm and 208 mm of rainfall, respectively, with corresponding SDs of 85 mm (40% CV) and 87 mm (42% CV).

Studies by Zubair and Ropelewski (2006) and Sreekala *et al*. (2011) indicate that El Niño events generally strengthen Northeast Monsoon (NEM) rainfall, while La Niña years tend to correspond with weaker monsoon performance. Table 2 shows that most El Niño years are associated with positive rainfall anomalies, reflecting favorable NEM performance, while La Niña years often lead to negative anomalies, indicating poor monsoon performance. Notably, 2010 and 2015-moderate and strong El Niño years, respectively-were marked by good monsoon seasons. However, the strong El Niño event of 2016, coupled with a negative Indian Ocean Dipole (IOD), disrupted typical northeast monsoon (NEM) patterns over southern peninsular India, resulting in unusually low rainfall. This deviation from expected NEM performance underscores the complex interplay between ENSO and IOD events. While a positive IOD phase usually enhances NEM rainfall, the negative IOD in 2016 likely suppressed it, revealing the need for deeper investigation into how these climate modes jointly

TABLE 2

Good and Poor Northeast Monsoon Years during 1871 to 2016

Subdivision/Area	Good monsoon years	Poor monsoon years
SP India	1883, 1884, 1887, 1893, 1902, 1903, 1922, 1925, 1930, 1939, 1940, 1943, 1944, 1946, 1956, 1966, 1969, 1977, 1987, 1993, 1994, 1997, 2005, 2010, 2015	1875, 1876, 1881, 1897, 1899, 1900 1904, 1908, 1909, 1926, 1927, 1938, 1947, 1949, 1951, 1965, 1974, 1984, 1988, 1989, 1995, 2016
Coastal AP	1878, 1880, 1882, 1883, 1886, 1893, 1903, 1915, 1919, 1925, 1930, 1931, 1939, 1944, 1946, 1956, 1958, 1962, 1969, 1972, 1976, 1987, 1994, 2010	1871, 1876, 1891, 1896, 1897, 1899, 1900, 1905, 1908, 1909, 1914, 1926, 1935, 1951, 1957, 1964, 1965, 1967, 1970, 1984, 1988, 1989, 2000, 2011, 2016
Rayala Seema	1874, 1880, 1882, 1883, 1884, 1893, 1903, 1912, 1916, 1922, 1930, 1937, 1940, 1946, 1956, 1972, 1975, 1987, 1991, 1993, 1996, 2001, 2005, 2015	1875, 1876, 1896, 1897, 1899, 1900, 1904, 1908, 1909, 1914, 1923, 1926, 1938, 1942, 1947, 1951, 1959, 1963, 1965, 1983, 1988, 1989, 1995, 2004, 2013, 2016
Tamil Nadu	1877, 1880, 1884, 1887, 1896, 1898, 1902, 1913, 1920, 1922, 1930, 1931, 1940, 1946, 1966, 1977, 1978, 1979, 1993, 1997, 2005, 2008, 2010, 2015	1976, 1878, 1879, 1886, 1889, 1892, 1897, 1904, 1909, 1917, 1926, 1927, 1938, 1947, 1949, 1950, 1952, 1974, 1986, 1988, 1989, 1995, 2016
South Interior Karnataka	1877, 1880, 1883, 1885, 1887, 1893, 1898, 1902, 1903, 1916, 1922, 1930, 1932, 1939, 1940, 1943, 1946, 1953, 1956, 1962, 1966, 1977, 1987, 1993, 1994, 1997, 1999, 2005, 2010	1875, 1876, 1897, 1899, 1907, 1908, 1913, 1923, 1924, 1926, 1927, 1938, 1945, 1959, 1965, 1985, 1988, 2013, 2016
Kerala	1877, 1891, 1901, 1902, 1910, 1912, 1914, 1919, 1920, 1925, 1930, 1932, 1942, 1943, 1946, 1955, 1966, 1972, 1977, 1987, 1993, 1997, 1998, 1999, 2002, 2010	1872, 1873, 1875, 1876, 1881, 1890, 1894, 1897, 1900, 1923, 1927, 1938, 1947, 1949, 1963, 1967, 1968, 1971, 1974, 1982, 1988, 1995, 2012, 2016

TABLE 3

Average Rainfall Amounts During Good and Poor Northeast Monsoons and Percentage Rainfall Departures

Sub-divisions	Event	SP India	Coastal AP	Rayalaseema	Tamil Nadu	SI Karnataka	Kerala
SP India	Good	481.8 (40%)	534.2 (41%)	312.3 (48%)	635.9 (39%)	333.3 (55%)	585.6 (21%)
	Poor	204.6 (-41%)	215.2 (-44%)	107 (-49%)	284.9 (-38%)	119.6 (-44%)	318.4 (-34%)
Coastal AP	Good	435.4 (26%)	589.1 (55%)	288.9 (37%)	518.4 (14%)	259.6 (21%)	545.4 (13%)
	Poor	242.8 (-29%)	172.9 (-54%)	113.4 (-46%)	390.9 (-14%)	151.3 (-30%)	398.1 (-17%)
Rayalaseema	Good	449.1 (30%)	516.7 (36%)	359.8 (70%)	556.2 (22%)	296.0 (37%)	541.7 (12%)
	Poor	229.4 (-33%)	222.4 (-41%)	87.1 (-59%)	361.6 (-21%)	124.4 (-42%)	357.1 (-26%)
Tamil Nadu	Good	455.6 (32%)	434.1 (14%)	273.7 (30%)	677.3 (48%)	280.3 (30%)	589.1 (22%)
	Poor	237.7 (-31%)	329.3 (-13%)	141.9 (-33%)	253.8 (-44%)	151.4 (-30%)	355.6 (-26%)
SI Karnataka	Good	462.7 (34%)	500.5 (32%)	305.1 (44%)	588.7 (29%)	339.6 (58%)	597.0 (54%)
	Poor	249.3 (-28%)	292.8 (-23%)	130.1 (-38%)	370.3 (-19%)	88.9 (-59%)	373.3 (-23%)
Kerala	Good	421.3 (22%)	417.9 (10%)	239.3 (13%)	568.7 (25%)	259.5 (20%)	693.2 (44%)
	Poor	249.9 (-27%)	316.6 (-17%)	150.1 (-29%)	342.3 (-25%)	141.0 (-35%)	267.1 (-45%)

influence monsoon variability (Kripalani and Kumar, 2004).

Table 2 also identifies specific active and poor NEM years for South Peninsular (SP) India and its five subdivisions: Coastal Andhra Pradesh, Rayalaseema, Tamil Nadu, South Interior Karnataka, and Kerala. Table 3 quantifies composite NEM rainfall across SP India and these subdivisions.

Coastal AP

In good monsoon years, Coastal Andhra Pradesh sees a substantial 55% rainfall surplus, with Rayalaseema

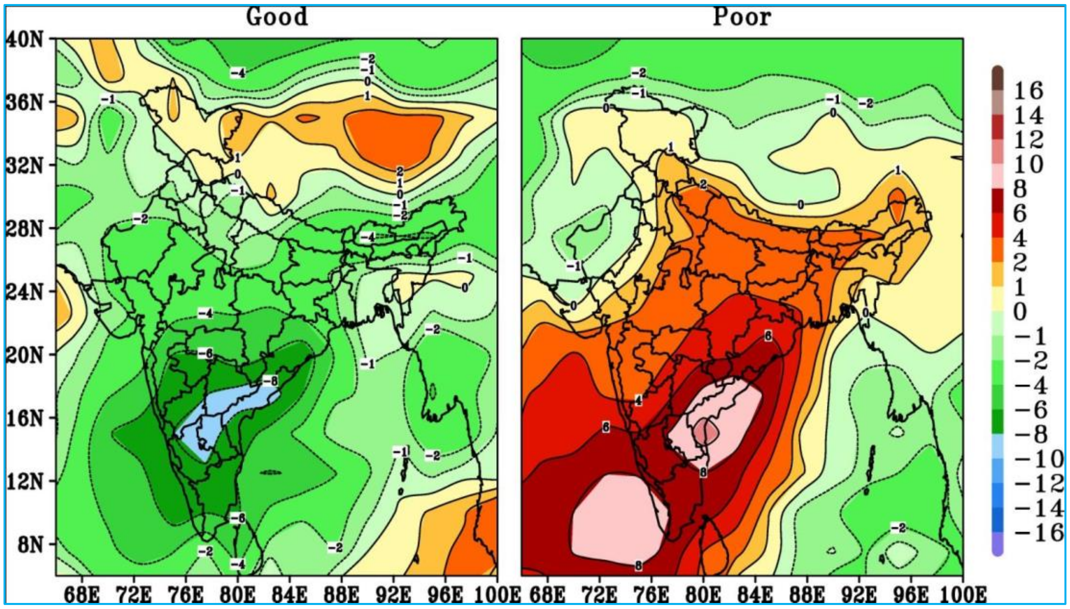


Fig. 1. Composite OLR anomalies for good and poor monsoons of Coastal AP

and SP India experiencing surpluses of 37% and 26%, respectively. South Interior Karnataka also benefits from a 21% surplus, while Tamil Nadu and Kerala record moderate surpluses of 14% and 13%. Conversely, during poor monsoon years, Coastal Andhra Pradesh suffers a 54% deficit, while Rayalaseema faces a 46% shortfall. South Interior Karnataka and SP India both show 30% deficits, with Tamil Nadu and Kerala showing slightly smaller deficits at 14% and 17%, respectively.

Rayalaseema

Rayalaseema exhibits substantial rainfall variability, with a 70% surplus during favorable NEM events. Coastal Andhra Pradesh and South Interior Karnataka see 36% and 37% surpluses, respectively, while SP India averages a 30% surplus. However, during poor NEM years, Rayalaseema encounters deficits between 21% and 59%, and South Interior Karnataka and Coastal Andhra Pradesh experience deficits of 42% and 41%.

Tamil Nadu

During favorable Northeast Monsoon (NEM) events, Tamil Nadu experiences a significant rainfall surplus of 48%, with this season contributing a substantial portion of the annual rainfall. NEM rains also influence nearby regions, with Rayalaseema, South Interior Karnataka, and South Peninsular India receiving approximately 30% of the excess rainfall from the Tamil Nadu monsoon. Kerala and Coastal Andhra Pradesh observe surpluses of 22% and 14%, respectively. In contrast, during poor monsoon years, Tamil Nadu shows a 44% rainfall deficit, while deficits in Rayalaseema, South Interior Karnataka, and SP India range from 30% to 33%. Kerala and Coastal Andhra Pradesh record deficits of 26% and 13%, respectively.

South Interior Karnataka

In active NEM years, South Interior Karnataka experiences a robust 58% increase in rainfall, while Kerala records a similar 54% surplus. Rayalaseema benefits from a 44% surplus and Tamil Nadu, Coastal Andhra Pradesh, and SP India see rainfall surpluses of 29%, 32% and 34%, respectively. However, during poor NEM years, South Interior Karnataka faces a pronounced rainfall deficit of 59%, while Tamil Nadu has a smaller deficit of 19%. Kerala and Coastal Andhra Pradesh show deficits of 23% each, while Rayalaseema and SP India face deficits of 38% and 28%, respectively.

Kerala

During favorable NEM seasons, Kerala experiences a 44% excess in rainfall, influencing rainfall distribution across SP India. Neighboring regions like Tamil Nadu, South Interior Karnataka, and Coastal Andhra Pradesh report surpluses of 25%, 20% and 10%, respectively. During poor NEM seasons, Kerala faces a 45% deficit, with deficits in South Interior Karnataka, Tamil Nadu, SP India, Rayalaseema, and Coastal Andhra Pradesh ranging from 17% to 35%. These rainfall patterns underscore the interconnectedness of these five subdivisions, collectively forming the SP India region.

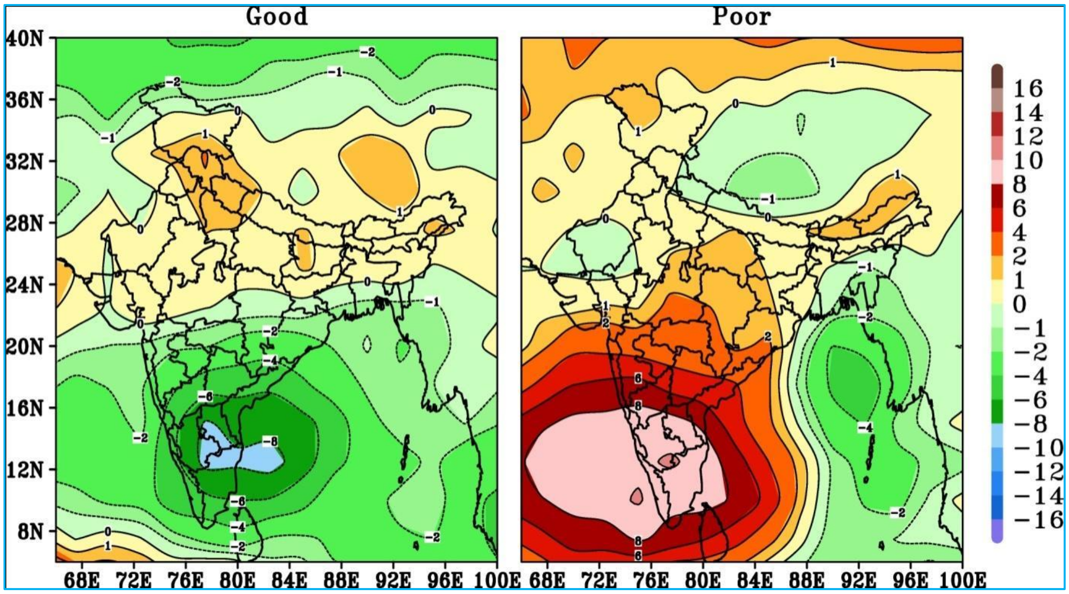


Fig. 2. Composite OLR anomalies for good and poor monsoons of Rayalaseema

South Peninsular India (SP India)

In active NEM years, SP India sees an overall 40% rainfall surplus, with higher surpluses in South Interior Karnataka (55%) and Rayalaseema (48%). Tamil Nadu and Coastal Andhra Pradesh experience about 40% surplus, while Kerala observes a more moderate 21%. Conversely, poor NEM years result in a substantial 41% rainfall deficit across SP India. Coastal Andhra Pradesh, Rayalaseema, and South Interior Karnataka show significant deficits of 43%, 49%, and 44%, respectively, while Tamil Nadu and Kerala record deficits of 38% and 34%.

3.2. *Composite OLR anomalies for active and poor monsoon years*

Fig. 1 illustrates the composite Outgoing Longwave Radiation (OLR) anomalies over Coastal Andhra Pradesh (AP) during active and poor NEM years. In good monsoon years, negative OLR anomalies dominate over southern mainland India and the Arabian Sea, indicating enhanced convection. These negative anomalies are particularly intense over Coastal AP, eastern Rayalaseema and northern Tamil Nadu, with values around -8 W/m², signifying strong convective activity. In contrast, poor monsoon years are characterized by widespread positive OLR anomalies dominate across the Indian mainland, reflecting reduced convective activity. Negative anomalies appear in the eastern Bay of Bengal and northwestern India. The highest positive anomalies, ranging from 8 to 10 W/m², are concentrated over Coastal AP, Rayalaseema, Tamil Nadu, Kerala, southern South Interior Karnataka, and the southeastern Arabian Sea, indicating weaker monsoon conditions and reduced convective activity in these regions. This contrast underscores the variability in convective activity and monsoon intensity between good and poor monsoon seasons over Coastal AP.

Fig. 2 highlights the composite Outgoing Longwave Radiation (OLR) anomalies over Rayalaseema for good and poor monsoon events. During good monsoon events, NEM seasons, Rayalaseema and South Coastal Andhra Pradesh exhibit pronounced negative OLR anomalies (-8 to -9 W/m²), indicating strong convective activity and substantial rainfall across South Peninsular India. Similar negative anomalies appear over the Bay of Bengal and the eastern Arabian Sea, further supporting high rainfall patterns in the region. In contrast, northwestern India shows slight positive anomalies (1 to 2 W/m²), suggesting less convective activity. Poor monsoon seasons, however, show a stark reversal. South Peninsular India, particularly Rayalaseema, South Interior Karnataka, Kerala, and southern Coastal Andhra Pradesh, display high positive OLR anomalies (8 to 12 W/m²), indicating weakened convection and reduced rainfall. Although overall monsoon conditions are weak, negative OLR anomalies (2 to 8 W/m²) over the eastern Bay of Bengal suggest some localized convective activity. This contrast in OLR anomalies underscores the variability in convective activity and rainfall between favorable and poor monsoon seasons in Rayalaseema and surrounding areas, reflecting the complex dynamics that drive rainfall variability across South Peninsular India.

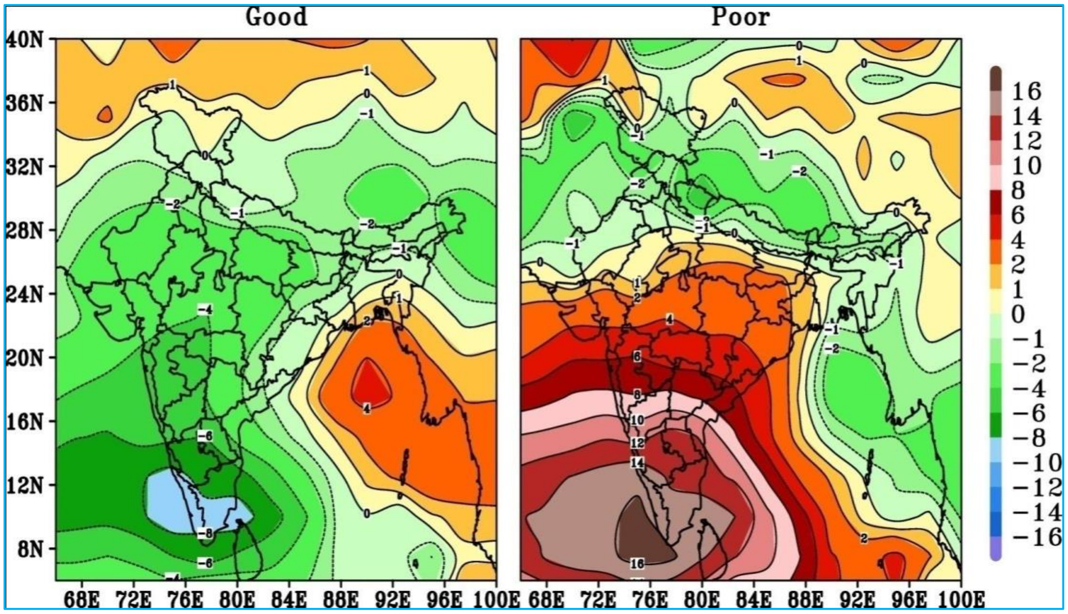


Fig. 3. Composite OLR anomalies for good and poor monsoon of Tamil Nadu

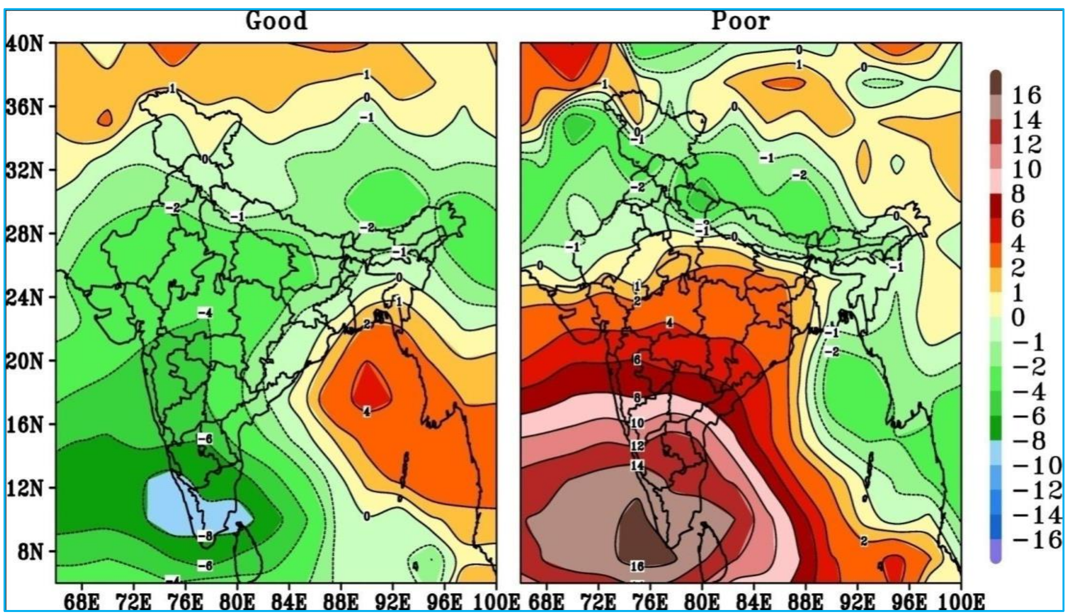


Fig. 4. Composite OLR anomalies for good and poor monsoons of South Interior Karnataka

Tamil Nadu

Fig. 3 illustrates the composite Outgoing Longwave Radiation (OLR) anomalies for Tamil Nadu during good and poor Northeast Monsoon (NEM) events. During good monsoons, negative OLR anomalies are widespread across India and the Arabian Sea, with Tamil Nadu, Kerala, and the adjacent Arabian Sea displaying significant negative values (-6 to -8 W/m²), indicating high convective activity and substantial rainfall. In contrast, positive anomalies are observed over the Bay of Bengal's northeastern areas and coastal regions north of 17° N, suggesting lower convective activity there.

During poor monsoon events, the pattern reverses: most of India, including Tamil Nadu and South Peninsular India, shows positive OLR anomalies, indicating reduced convection and lower rainfall. Kerala, the southeastern Arabian Sea, Tamil Nadu, southern Coastal Andhra Pradesh, Rayalaseema, and South Interior Karnataka

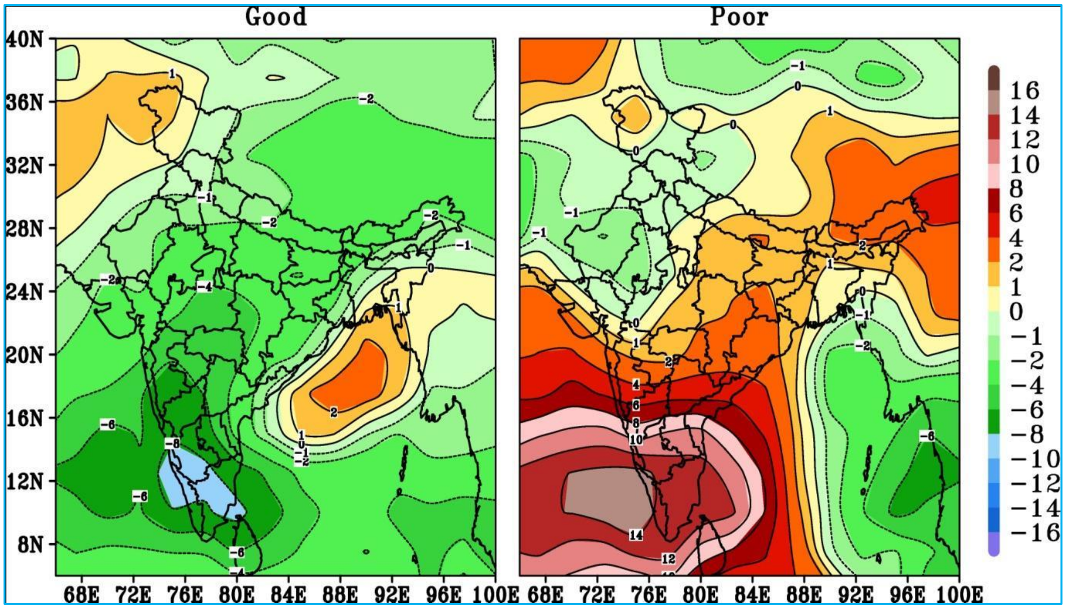


Fig. 5. Composite OLR anomalies for active and poor monsoons in Kerala

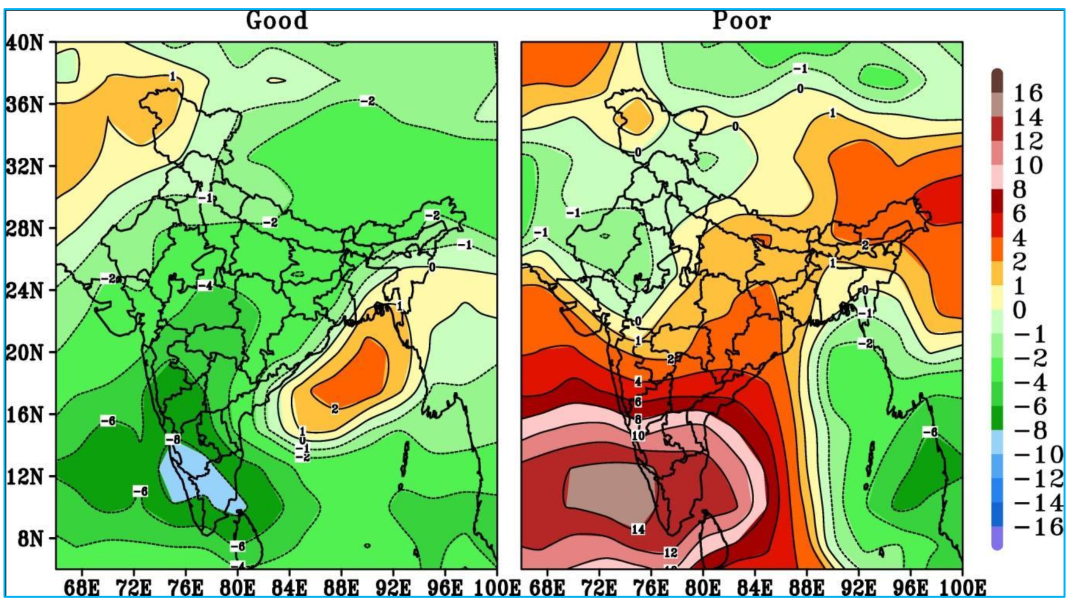


Fig. 6. Composite OLR anomalies for good and poor monsoons of SP India

exhibit the highest positive anomalies (6–8 W/m²). This shift in anomalies underscores the marked reduction in rainfall during poor monsoons compared to favorable ones.

South Interior Karnataka

Fig. 4 shows composite OLR anomalies over South Interior Karnataka for active and poor NEM years. During active monsoon events, negative OLR anomalies dominate across India, particularly over South Peninsular India. South Interior Karnataka, Tamil Nadu, and Kerala display strong negative anomalies (-8 W/m²), reflecting intense convective activity and enhanced rainfall. Positive anomalies are observed over the eastern Bay of Bengal and the northeastern Arabian Sea, suggesting reduced convection in these areas.

In poor NEM years, positive OLR anomalies cover major parts of South Peninsular India, especially South

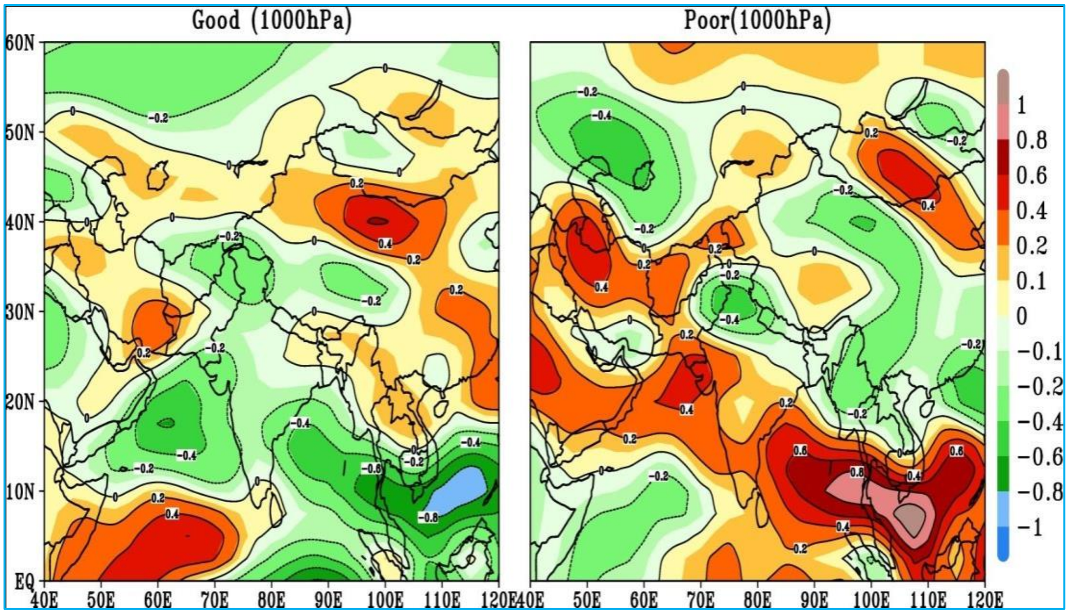


Fig. 7. Composite zonal wind anomalies for good and poor monsoons of South Peninsular India at 1000 hPa and 850 hPa

Interior Karnataka, North Interior Karnataka, Coastal Karnataka and Rayalaseema, indicating weaker convection and diminished rainfall.

Kerala

Fig. 5 shows OLR anomalies for Kerala, where active NEM events are marked by intense negative anomalies, particularly over Kerala, the southeastern Arabian Sea, and southern Tamil Nadu (-8 W/m²). These negative anomalies reflect heightened convective activity and abundant rainfall. Conversely, during poor NEM years, positive anomalies dominate across the Indian mainland and adjacent sea regions. Kerala, Tamil Nadu, and parts of Coastal Andhra Pradesh show the highest positive values, suggesting reduced rainfall across South Peninsular India.

South Peninsular India (SP India)

In active monsoon seasons, Figure 6 reveals widespread negative OLR anomalies over SP India, concentrated over Tamil Nadu, Karnataka, Kerala, and Rayalaseema (-8 to -10 W/m²), indicating strong convective activity. Positive anomalies are observed in the Andaman and Nicobar Islands, parts of the Bay of Bengal, Gujarat, and the Arabian Sea, suggesting limited convection in those areas.

In poor monsoon seasons, positive OLR anomalies dominate SP India (8 to 12 W/m²), especially over southeastern Arabian Sea, southern Kerala, and Tamil Nadu, reflecting weakened monsoon conditions. Negative anomalies appear over the eastern Bay of Bengal and parts of northwestern India.

3.3. *Composite zonal wind anomalies for good and poor monsoons*

The NECP/NCAR Reanalysis wind data, spanning from 1948 to 2016, was analyzed for the Northeast Monsoon (NEM) period (October–December) over a geographic domain from 40° E to 120° E longitude and 0° N to 60° N latitude. This analysis focused on composite mean circulation patterns at 1000 hPa, 850 hPa and 200 hPa for favorable and poor monsoon years in South Peninsular India. Anomalies were calculated by subtracting the long-term mean from these composites to capture deviations in both favorable and poor monsoon years.

During favorable monsoon years, 1000 hPa zonal wind anomalies are predominantly negative across the Bay of Bengal, Arabian Sea and much of India, especially south of 20°N and in the northwest, indicating enhanced easterly flows. These anomalies are most pronounced in the central Bay of Bengal (-0.6 m/s) and the Arabian Sea (-0.4 m/s). In contrast, the Western Equatorial Indian Ocean shows positive anomalies (0.2 to 0.4 m/s), while negative anomalies are observed in the Eastern Equatorial Indian Ocean. This pattern reflects an intensification of easterly winds, facilitating moisture transport to the

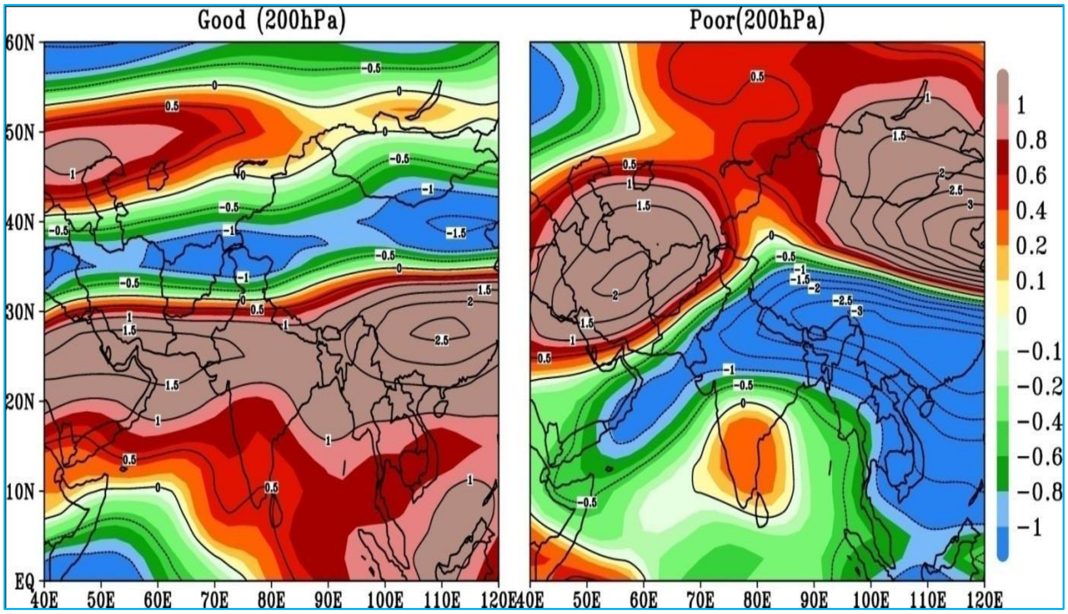


Fig. 8. Composite zonal wind anomalies for good and poor monsoons of SP India at 200 hPa

Intertropical Convergence Zone (ITCZ) and promoting increased tropical disturbances and rainfall over southeastern India (Fig. 7).

In poor monsoon years, this pattern at 1000 hPa is reversed. Positive anomalies dominate the Bay of Bengal, the northern Arabian Sea, and much of India (24° N-8° N), with values in the Bay of Bengal reaching 0.3 to 0.9 m/s, indicating weakened easterly winds and reduced moisture transport to the ITCZ.

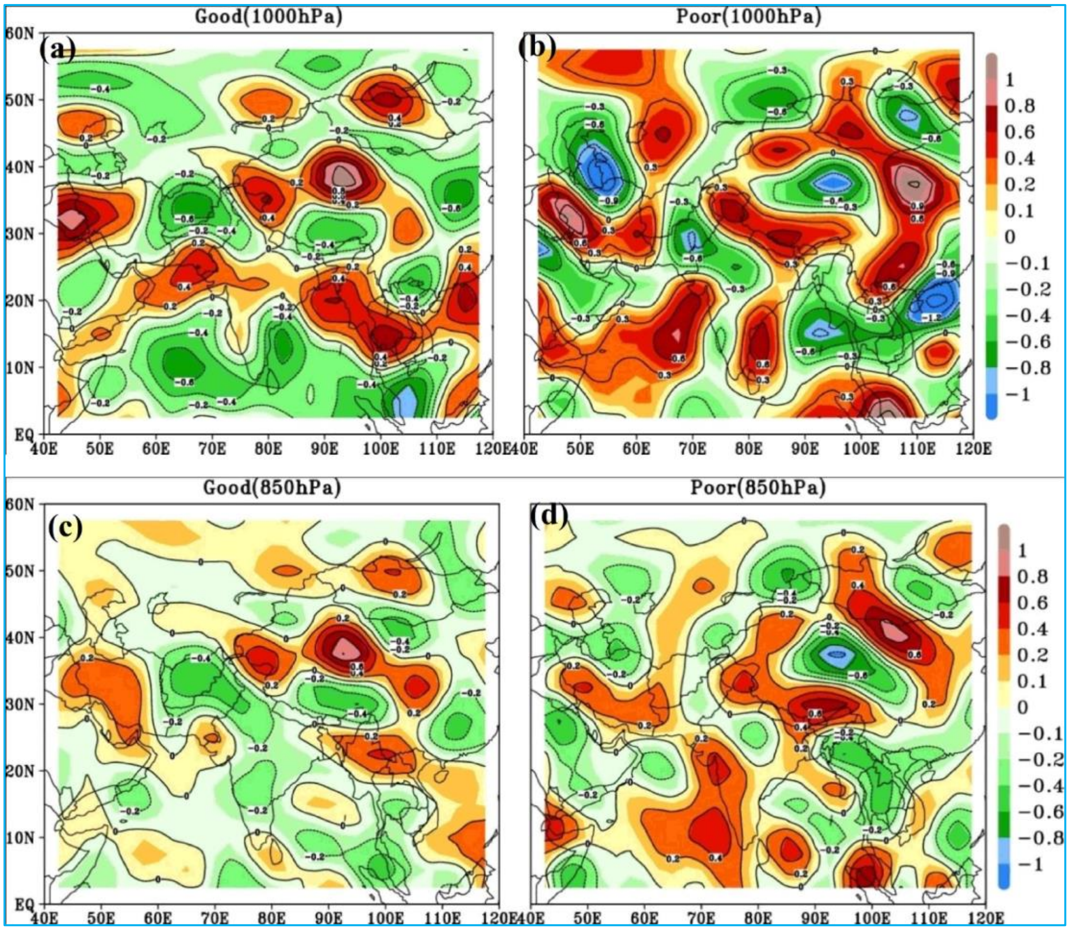
At 850 hPa, favorable monsoon years exhibit negative wind anomalies over the Bay of Bengal, Arabian Sea, and most of India, with values ranging from -0.6 to -0.9 m/s in the central Bay of Bengal and up to -3.0 m/s in the central Arabian Sea. Positive anomalies appear in northeast India and the Western Equatorial Indian Ocean, while negative anomalies are observed in the Eastern Equatorial Indian Ocean. In poor monsoon years, these patterns reverse: positive anomalies are prevalent over the Bay of Bengal, much of India, and the Andaman and Nicobar Islands, while negative anomalies appear in northern and northeastern India and the Western Equatorial Indian Ocean.

At 200 hPa, during favorable monsoon years in South Peninsular India, westerly wind anomalies are prominent over India, the Arabian Sea, the Bay of Bengal, and the Indian Ocean. The strongest positive anomalies, reaching up to 2.5 m/s, are concentrated between 103° E to 120° E and 26° N to 31° N, indicating a significant intensification of the westerly jet over India. This intensification supports enhanced rainfall across South Peninsular India, with totals ranging from 433 to 516 mm. The increased rainfall releases latent heat through condensation, warming the atmosphere and strengthening the north-south temperature gradient, which further intensifies the westerly jet (Fig. 8).

This pattern of stronger westerly jet activity aligns with the global warming period, which began around 1970. During this era, warming has been more pronounced at southern latitudes near the equator than in the Northern Hemisphere, enhancing moisture transport and intensifying the northeast monsoon over India. Conversely, in poor monsoon years, this anomaly pattern at 200 hPa is reversed, with negative anomalies over northern India. The strongest negative anomalies, ranging between 10° E to 120° E and 20° N to 27° N, reflect a weakened westerly jet stream. In these years, lower rainfall results in less atmospheric heating, diminishing the temperature gradient and weakening the westerly jet (Fig. 8).

3.4. *Composite divergence anomalies for good and poor monsoons*

Fig. 9 shows divergence anomalies at 1000 hPa and 850 hPa for both favorable and poor monsoon years over South Peninsular India. During favorable monsoon years, negative divergence anomalies are prominent at 1000 hPa



Figs. 9(a-d). Composite divergence anomalies for good and poor monsoons of SP India at 1000 hPa and 850 hPa

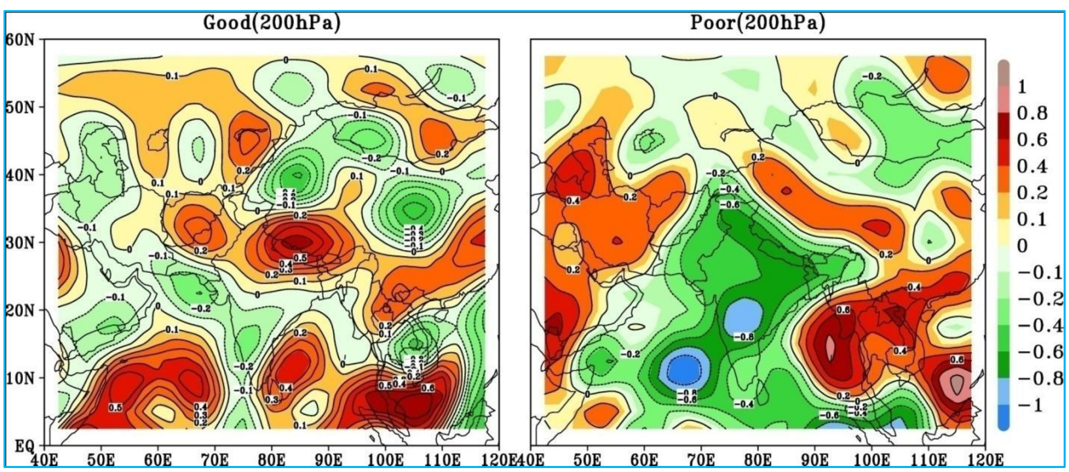
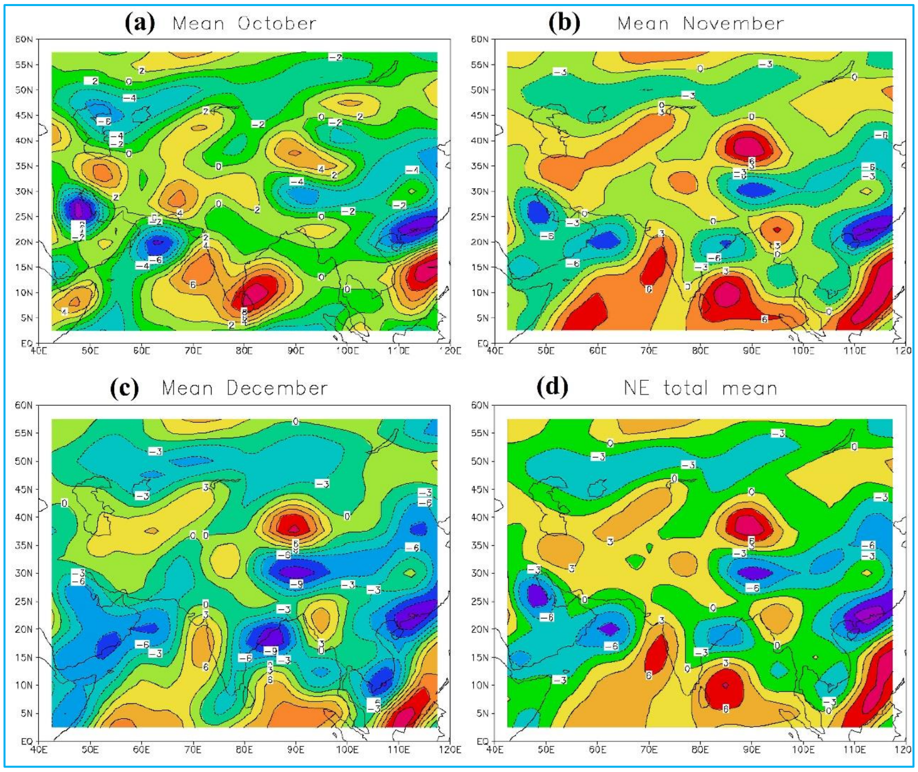


Fig. 10. Composite divergence anomalies for good and poor monsoons of SP India at 200 hPa

over the southern Bay of Bengal, the northeast monsoon region of South India, northern India, the Arabian Sea, the equatorial Indian Ocean and Indonesia. In contrast, positive anomalies appear from Saudi Arabia to the South China Sea, spanning the northern Arabian Sea, Gujarat, West Bengal, the northern Bay of Bengal, Myanmar, and



Figs. 11(a-d). Mean Relative Vorticity at 1000mb in different months and northeast monsoon season

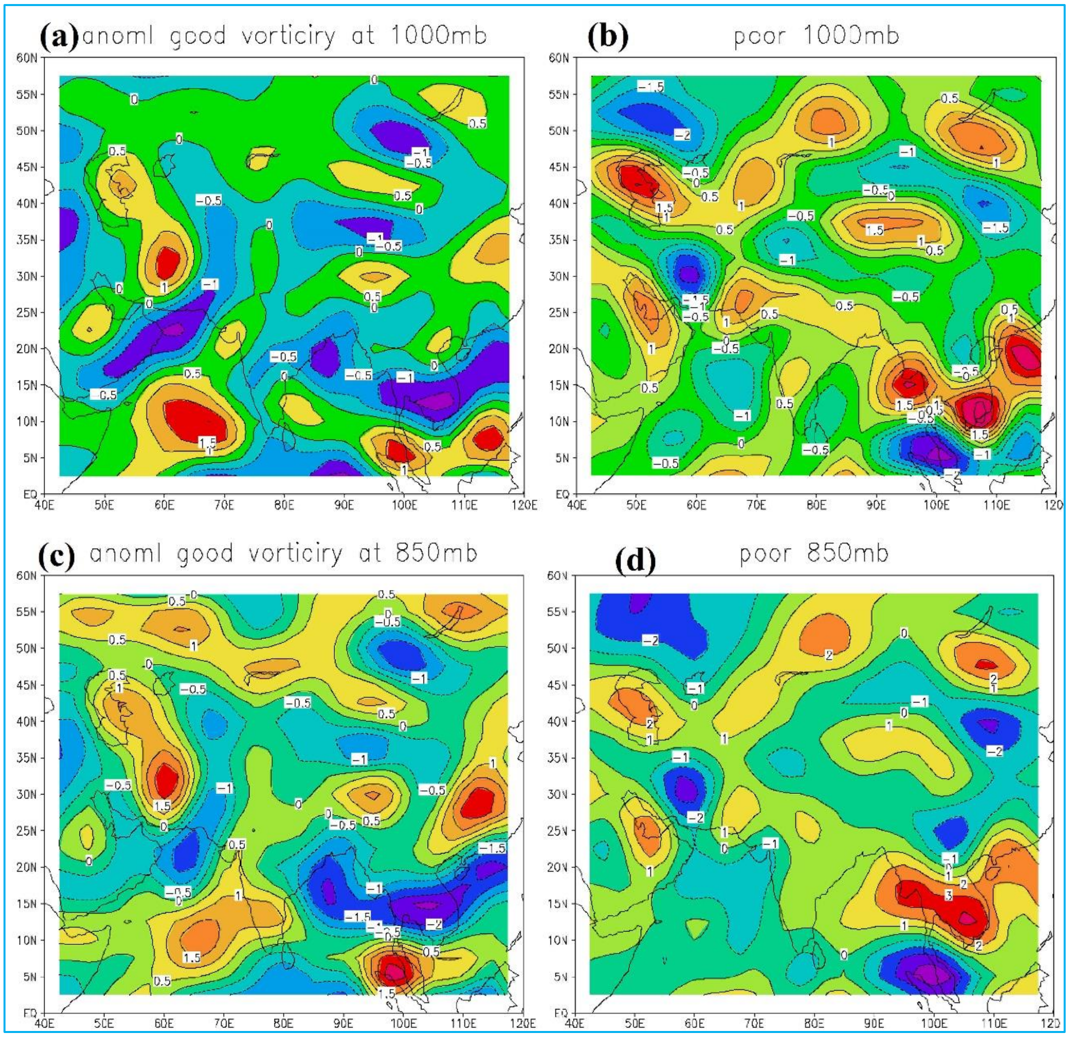
Vietnam at around 20° N to 25° N. In poor monsoon years, this pattern reverses: positive divergence anomalies are observed over the northeast monsoon region of India, the east coast, the Bay of Bengal, the Arabian Sea extending toward Kazakhstan and parts of southern and eastern China. Negative anomalies stretch from Gujarat through South China, passing over Madhya Pradesh, Bangladesh, Myanmar, and Vietnam.

At 850 hPa, favorable monsoon years display negative divergence anomalies over the southern Bay of Bengal, the central Arabian Sea, and a major part of India, suggesting enhanced convergence and convective activity. Positive anomalies are found in the northwestern and northeastern parts of India, as well as in Myanmar, Vietnam and the South China Sea. These distinct divergence patterns underscore the marked differences in atmospheric circulation between favorable and poor monsoon seasons in South Peninsular India.

Fig. 10 presents composite divergence anomalies at 200 hPa for favorable and poor monsoon years over South Peninsular India. In favorable monsoon years, negative divergence anomalies-indicating enhanced convergence are prominent across much of India south of 25° N, the northern Bay of Bengal, Thailand, Vietnam, Cambodia, large parts of China, Ethiopia and surrounding areas. Positive divergence anomalies, which suggest weaker convergence, are observed from the northwestern to northeastern regions of India and over the Arabian Sea south of 15° N, extending toward Indonesia from the Bay of Bengal.

In contrast, during poor monsoon years, negative anomalies dominate over most of India, the Arabian Sea, and the eastern equatorial Indian Ocean, reflecting reduced convective activity. Positive anomalies stretch from the eastern Bay of Bengal to the South China Sea and are also seen over Somalia, Saudi Arabia, and nearby regions. These distinct anomaly patterns underscore the significant differences in atmospheric circulation and convergence between favorable and poor monsoon seasons.

The Fig. 11 shows the mean relative vorticity at 1000 hPa for October, November, December and the overall Northeast monsoon season. In October, cyclonic vorticity is observed over southern India, with maximum concentrations over the southwestern Bay of Bengal and the east central Arabian Sea, extending to 115° E, 14° N. The entire South Peninsular India is influenced by positive vorticity, while negative vorticity stretches from the



Figs. 12(a-d). Composite vorticity anomalies at 1000 and 850 hPa in active and poor monsoon years of SP India

northern Arabian Sea to Southeast China through Gujarat, Orissa, and the Head Bay of Bengal., In November, cyclonic vorticity shifts slightly within the south Bay of Bengal and extends from the western equatorial Indian Ocean to the east central Arabian Sea. Southern South Peninsular India and the northeastern parts of India experience positive vorticity, while negative vorticity extends from Kuwait/Saudi Arabia to Southeast China via the north Arabian Sea, Gujarat, Orissa, north Bay of Bengal, and Vietnam. December sees the cyclonic vorticity in the Bay of Bengal move further south, with intensified anticyclonic vorticity over India and the northeastern parts. Positive vorticity extends from Maharashtra to the equatorial Indian Ocean and negative vorticity persists along the east coast of India and from Kuwait/Saudi Arabia to Southeast China. During the Northeast monsoon season, anticyclonic vorticity spans from northwestern China to the South China Sea, passing through Orissa, the northern Bay of Bengal, Thailand, and Vietnam. Cyclonic vorticity is organized over the Bay of Bengal, the eastern Arabian Sea, and the northeastern parts of India, while negative vorticity extends from Saudi Arabia to the northern Arabian Sea.

3.5. *Composite vorticity anomalies in good and poor monsoons*

The Fig. 12 illustrates composite vorticity anomalies at 1000 hPa and 850 hPa for good and poor monsoons in South Peninsular India. During good monsoons, at 1000 hPa, negative vorticity anomalies are concentrated in the northern Arabian Sea, southernmost parts of India, adjacent Indian Ocean, Head Bay of Bengal and northeastern parts of India. Positive anomalies are found between 5° N and 15° N, indicating an intensified ITCZ and anticyclonic cell over northern regions. High cyclonic

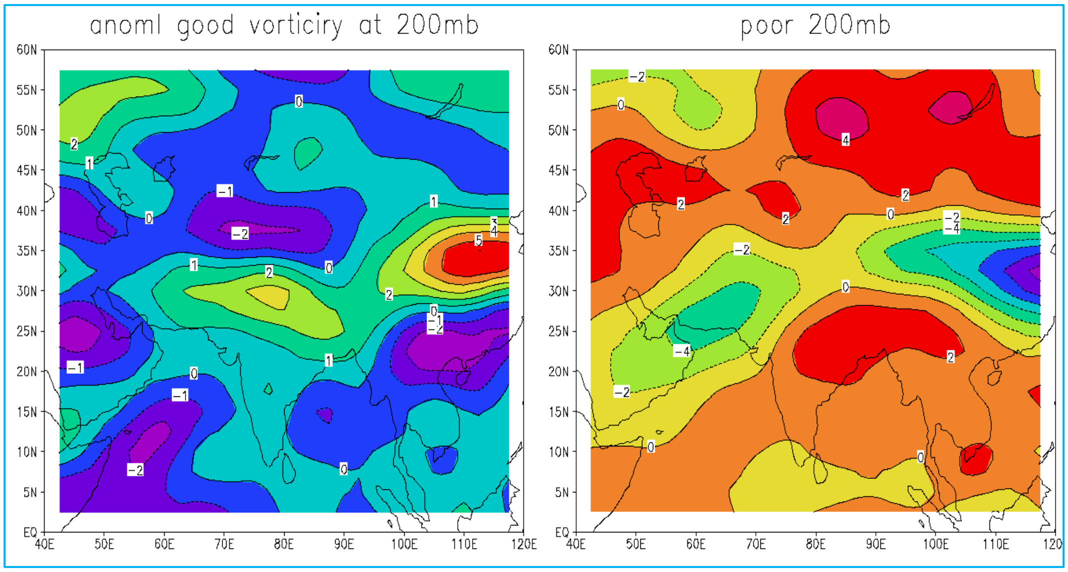


Fig. 13. Composite vorticity anomalies at 200 hPa in active and poor monsoon years of SP India

vorticity is present in the southern Arabian Sea. Conversely, in poor monsoons, positive anomalies dominate over northern India, while anticyclonic circulation is prevalent across the Arabian Sea and from the southwestern Bay of Bengal to Indonesia. Anomalous cyclonic vorticity extends from Saudi Arabia to the South China Sea, passing through regions including the North Arabian Sea, Gujarat, Orissa, Bangladesh, Head Bay of Bengal, and Vietnam, indicating a weakened ITCZ and anticyclonic cells.

At 850 hPa, good monsoons show a dipole structure in the Bay of Bengal and equatorial Indian Ocean, with anticyclonic anomalies in the north and cyclonic anomalies in the south. In the Arabian Sea, northwestern parts exhibit negative vorticity anomalies, while southeastern parts show positive anomalies. This pattern indicates an intensified ITCZ and anticyclonic cells. In poor monsoons, this dipole pattern is reversed, reflecting a weakened ITCZ and anticyclonic cells. These variations underscore the distinct vorticity anomaly patterns in good and poor monsoon years, highlighting the differences in the intensity and positioning of the ITCZ and anticyclonic cells over South Peninsular India and neighbouring regions.

The Fig. 13 illustrates composite vorticity anomalies at 200 hPa for good and poor monsoons in South Peninsular India. In good monsoon years, cyclonic vorticity anomalies extend from the Red Sea to eastern South China, passing through northern India, with negative anomalies over the southwest Bay of Bengal, the South China Sea, and Myanmar. Anticyclonic anomalies are present in the southwest Arabian Sea.

In poor monsoon years, anticyclonic vorticity anomalies extend from Saudi Arabia to eastern South China, passing through northern India, with positive anomalies over the southwest Bay of Bengal, the South China Sea and Myanmar. Cyclonic anomalies are observed in the southwest Arabian Sea. These patterns indicate the presence of an intensified or weakened subtropical ridge, highlighting the variability in atmospheric circulation during different monsoon intensities.

4. Conclusions

The analysis of the Northeast Monsoon (NEM) from 1871 to 2016 reveals distinct regional rainfall patterns across South Peninsular India. On average, the NEM brings 344 mm of rainfall with a coefficient of variation (CV) of 26%. The rainfall distribution varies significantly across the five meteorological subdivisions: Kerala and Tamil Nadu receive the most rainfall, with 482 mm and 456 mm respectively, and CVs of 31% each. In contrast, South Interior Karnataka and Rayalaseema report much lower averages of 215 mm and 211 mm, with CVs of 40% and 42%. The study also uncovers substantial variability in rainfall during both active and poor NEM periods. Coastal Andhra Pradesh, for instance, experiences deficits ranging from 14% to 54%, while surpluses can range from

13% to 55%. Rayalaseema sees deficits from 21% to 59% and surpluses between 12% and 70%, while Kerala's rainfall varies with deficits ranging from 17% to 45% and surpluses from 10% to 44%. This regional variability underscores the complexity of the NEM and its uneven impacts across South Peninsular India. Further analysis of Outgoing Longwave Radiation (OLR) anomalies highlights the connection between convection and rainfall. Negative OLR anomalies, indicative of enhanced convection, are observed during active monsoon years, resulting in higher rainfall, while positive OLR anomalies during poor monsoons reflect reduced convection and lower rainfall. Zonal wind anomalies provide additional insight into atmospheric circulation patterns. Negative zonal wind anomalies at 850 hPa and 1000 hPa during favorable monsoons suggest intensified easterly winds, promoting increased moisture transport. In contrast, positive anomalies during poor monsoons point to weakened easterly flow. At 200 hPa, westerly wind anomalies associated with a stronger westerly jet during active monsoons contribute to enhanced rainfall, further intensified by the release of latent heat and condensation that strengthen the north-south temperature gradient. Divergence anomalies at 1000 hPa and 850 hPa show a consistent pattern : negative anomalies during good monsoons are linked to enhanced convection and higher rainfall, while positive anomalies during poor monsoons correlate with reduced convection and lower rainfall. These trends are also observed at 200 hPa, reinforcing the connection between atmospheric divergence and monsoon intensity. In conclusion, this study underscores the intricate dynamics of the Northeast Monsoon, emphasizing the complex interplay between atmospheric circulation patterns, convection, and regional rainfall variability. A deeper understanding of these factors is essential for improving monsoon predictions and more effectively managing water resources across South Peninsular India.

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Authors' Contributions

G. Ch. Satyanarayana: Supervision, Methodology, Data Curation, Software, Conceptualization, Formal Analysis, Visualization, Writing – Original Draft, Review & Editing.
Sambasivarao Velivelli and Ch. L. Prasanna: Data Curation, Software, Conceptualization, Visualization, Review & Editing.
A. Dharma Raju and C. V. Naidu: Writing – Review & Editing.

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